PATENT

ANTI-G PRESSURE REGULATOR FOR SUPPLYING BREATHABLE GAS TO A PILOT'S FACE MASK AND METHOD

RELATED APPLICATION

This application claims the benefit of the filing date of provisional application number 60/274,332, filed March 8, 2001, entitled ANTI-G PRESSURE REGULATOR FOR SUPPLYING BREATHABLE GAS TO A PILOT'S FACE MASK AND METHOD as to all common subject matter.

FIELD OF THE INVENTION

The present invention relates to life support equipment and methods for providing physiological protection to pilots and astronauts when subjected to high g-force maneuvers.

BACKGROUND OF THE INVENTION

Modern aircraft are capable of maneuvers which can impose multiple gravity ("g") forces which exceed the physiological protection provided by state of the art life support equipment. Such equipment includes an anti-g suit with pneumatic bladders surrounding a major portion of a pilot's legs, thighs and abdomen, which when inflated impede the flow of blood to the lower extremities and abdomen. In addition, a chest bladder is often used to restrain excess chest expansion during the inhalation of oxygen (or oxygen enriched air) at elevated pressures. A mask, fitted over the pilot's nose and mouth, receives oxygen or a mixture of oxygen and air under a pressure proportional to the g-force loading to which the pilot is subjected.

A typical anti-g equipment arrangement for use by combat and test pilots is illustrated in Fig. 1 in which a source 11 of a suitable gas, such as air under a suitable pressure from an aircraft's compressor is connected to a pressure regulator 12. A source 10 of oxygen or oxygen enriched air (hereinafter collectively referred to as O_2) under a suitable high pressure, e.g., 1.5 to 10.0 atmospheres or about 22 to 150 psi, is connected to separate pressure regulator 12. The regulator 12 supplies the air, via line 16, to a conventional anti-g suit 18 which fits over the legs and lower abdomen of the pilot. The anti-g suit includes a series of inflatable bladders 18a. The regulator 14 supplies O_2 to a chest bladder 20 and a face mask 22 via line 24.

Conventional g-force sensors (not shown) control the regulators 12 and 14 so that the output pressures thereof are a function of the g-forces to which the pilot is being subjected. Fig. 2 illustrates, via curve 24, the typical pressure in millimeters, of Hg (ordinate) applied to the anti-g suit as a function of the g-force (abscissa). As is illustrated, the pressure curve 24 is essentially linear with changes in the g-force loading from about 1 g to about 10 g's.

Fig. 3 illustrates, via curve 26, the typical pressure in inches of water (ordinate) applied to the chest bladder and the inlet to the mask as a function of the g-force loading. From about 4 g's to 10 g's the curve is essentially linear.

The mask 22 is provided with a conventional inhalation and exhalation valves (not shown). The exhalation valve remains closed until the pressure of the gas to be exhaled exceeds the positive pressure being supplied by the regulator 14. The pilot must therefore exert sufficient pressure on his or her lungs during the exhalation phase to overcome the positive supply pressure. The maximum exhalation pressure may exceed the supply pressure by 5 to 6 inches of H_2O during a normal breathing cycle. A typical pilot's inhalation and exhalation phases, using the conventional anti-g equipment, is illustrated in Fig. 4 where the line 28 represents one value of positive supply pressure (as measured along the ordinate) and the curve 30 represents the pressure in the mask during the pilot's inhalation (t_o - t_1) and exhalation (t_1 - t_2) phases. As is noted by the curve 30 the pressure in the mask follows a sinusoidal

type curve during the breathing cycle. The extent of the fluctuations in mask pressure from the supply pressure depend on the gas capacity of the system and on the resistance of the mask regulator system. Such a state of the art system is discussed in several articles entitled *Combined Advanced Technology Enhanced Design G-ensemble; Advanced Technology Anti G-Suit; and Combat Edge Aircrew Positive Pressure Breathing System* published by the Brooks Scientific and Research Center of Space Medicine in San Antonio, Texas and posted on its website at http://www.brooks.af.mil/HSW/products/edge.html.

At high g-forces, e.g., above 3-4 g's, the state of the art anti-g equipment provides a constant positive pressure in the mask and vest. Such a pressure mode places little stress on a pilot's system during inhalation. However, the positive pressure in the lungs and internal chest pressure causes the diaphragm to lower. In order to raise the diaphragm and help the breathing muscles to perform an exhalation and subsequent inhalation exercise it is necessary for the pilot to strain and release the abdominal muscles periodically. This is especially difficult at very high g-forces. With abdominal muscles in a strained condition and an impaired or non-functioning diaphragm, the breathing muscles cannot provide normal breathing. The exhalation and inhalation phases become shorter, i.e., the breathing rate and lung ventilation increase. The velocity of air flow through the exhalation valve increases during the shortened inhalation phase resulting in a higher resistance to exhalation which may reach 9-10mm of mercury column. The increased stress not only causes the pilot to feel fatigue, but degrades his or her performance. At the same time blood slowly moves down from the brain as his or her higher heart rate indicates.

State of the art anti-g systems typically provide satisfactory physiological protection during force loads up to 8 - 9 g's for only 30 to 40 seconds.

As a result, such conventional anti-g equipment will not accommodate the full performance capabilities of modern fighter aircraft. Thus, due to the limited time of high g tolerance, the pilot must restrict the aircraft's performance to levels below its rated capabilities or run the risk of suffering sever fatigue at best or losing control

of the aircraft at worst. In addition, the constant positive exhalation pressure at high g loads severely limits or precludes two-way radio communication with the attendant disadvantages thereof during maneuvering. Also pilots experience extreme discomfort when breathing at high g loads with the result that their physical condition may be impaired for some time after the cessation of a high g maneuver.

A pilot's breathing rate is typically drastically increased by the higher exhalation resistance (Fig. 4), e.g., 40-50+ liters/min at 7-9 g force loads versus about 20 liters/min at no g load. Very often pilots complain of feeling severe pain in their hand joints due to the lack of compensating pressure. Immediately after long term exposure to high g forces, pilots have pointed out that their breathing does not return to normal for some time and that several days of rest may and often are required for rehabilitation after an intensive workout during flight. The long term effects on a pilot's health resulting from the wear and tear on the organisms, e.g., those involved in the breathing and cardiovascular systems which results from regular g force overloads over an extended period have not been determined.

There is an urgent need to provide combat and test pilots with greater physiological protection from the effects of high g maneuvers.

SUMMARY OF THE INVENTION

In accordance with the present invention a pilot is equipped with an anti-g suit which is inflated from a pressurized gas, e.g., air, in accordance with the g forces being experienced by the pilot in a conventional manner.

A method and apparatus of overcoming the shortcomings of conventional anti-g equipment for providing physiological protection for pilots when subjected to high g-forces includes the use of an inhalation valve connected between a pressurized source of O_2, an inlet/outlet port of the pilot's face mask and a chest bladder.

An exhalation valve is connected between the inlet/outlet port and a low pressure region such as the aircraft cabin interior. The inhalation and exhalation valves are opened and closed, respectively, during the inhalation phase of the pilot's spontaneous breathing cycle while the pressure of the O_2 supplied to the inlet/outlet

port is controlled so that the pressure rises from a predetermined minimum to a predetermined maximum as determined by the g force load to provide an increased volume of breathable O_2 to the pilot's lungs. The exhalation and inhalation valves are opened and closed, respectively, during the exhalation phase while the pressure in the inlet/outlet port is allowed to fall from the predetermined maximum to the predetermined minimum. The minimum pressure having a value less than the maximum for g-forces in excess of a selected value, e.g., 2.5 - 4 g's,. Preferably the maximum pressure is within a range of about 7 to 10 inches of water at about a 2.5 g force and within a range of about 20 to 30 inches of water at about a 9 g force. The minimum pressure is preferably within a range of about 12 to 18 inches of water less than the maximum pressure for g-loads above about 4 g's. The invention may employ a pneumatic system for controlling the functions (i.e., opening/closing) of the inhalation and exhalation valves as well as controlling the maximum and minimum pressures pursuant to a g-force sensor. Alternatively the invention may employ electrically operated variable flow (pressure) inhalation and exhalation valves responsive to the fluid flow path in the inlet/outlet port and the g force load as detected, for example, by a conventional electronic accelerometer. Optionally, the pressure of the gas supplied to the anti-g suit is nonlinear with respect to the g load over the anticipated g load range, e.g., the rate of pressure increase in the anti-g suit is higher during acceleration from low g loads to intermediate g loads and lower during acceleration from intermediate to high g-loads.

The present invention serves to maintain the parameters of a pilot's circulation system in a permissible range for high g-forces thereby enabling the pilot to tolerate such g forces for extended periods with less stress. The present invention also enables a pilot to achieve improved performance while requiring considerably less rehabilitation time after flight as compared with the use of state of the art equipment.

The construction and operation of the present invention may be best understood in reference to the following description taken in conjunction with the

accompanying drawings wherein like components are given the same reference number.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram of a conventional anti-g apparatus for use by combat and test pilots;

Fig. 2 is a graph illustrating a typical anti-g suit pressure versus g-force for the equipment of Fig. 1;

Fig. 3 is a graph illustrating a typical gas supply pressure to the pilot's face mask and chest bladder versus g-force for the equipment of Fig. 1;

Fig. 4 is a graph illustrating a pilot's typical breathing cycle when using the equipment of Fig. 1 with a positive pressure supplied to the mask to compensate for a high g force;

Fig. 5 is a schematic cross-sectional view of a pneumatic valve assembly in accordance with the present invention for controlling the ingress and egress of breathable gas to a pilot's face mask with the inhalation and exhalation valves shown in their closed positions;

Fig.6 is a graph showing, as an example, a maximum and minimum pressure as supplied to the inlet/outlet port of the mask of Fig. 5 and chest bladder in inches of H_20 versus g forces;

Fig. 7 is a graph of a typical breathing cycle of a pilot employing the apparatus of this invention with the maximum and minimum pressures, of Fig. 6, imposed in the mask inlet/outlet port;

Figs.8 a, b, and c are graphs showing the actual breathing cycles of an individual employing the apparatus of this invention at g-forces of 5, 7, and 9, respectively;

Figs. 9 a, b, and c are graphs of waveforms illustrating a typical breathing rate in breaths/minute of an individual using conventional anti-g equipment (curve A) versus using the present invention (curve B) at g-forces of 5, 7, and 9, respectively;

Figs. 10 a, b, and c are graphs showing the typical pulse rate of an individual

using conventional anti-g equipment (curve A) versus using the present invention (curve B) at g-forces of 5, 7, and 9, respectively;

Figs. 11 a, b, and c are graphs showing the typical lung ventilation rate of an individual using conventional anti-g equipment (curve A) versus using the present invention (curve B) at g-forces 5, 7, and 9, respectively;

Fig. 12 is a block diagram of an alternative embodiment in the form of an electronic/pneumatic apparatus for controlling the ingress and egress of breathable gas to and from the mask and chest bladder;

Fig. 13 is a graph illustrating an optimal schedule of anti-g suit pressure with increasing gravity forces and an approximation of such schedule using a regulator in accordance with the invention;

Fig. 14 is a diagrammatic diagram of a pneumatic pressure regulator for supplying pressure to a pilot's anti-g suit; and

Fig. 15 is a graph illustrating the operation of the two g-load sensors incorporated into the regulator of Fig. 14..

DESCRIPTION OF THE PREFERRED EMBODIMENT

The Pressure Regulating Pneumatic Valve Assembly

Referring now to Fig. 5 a face mask 32, covering the pilot's nose and mouth area, includes an inlet/outlet port 34 which receives O_2 from the pressurized source 10 via a valve block assembly 36. The valve block 36 includes a high pressure duct or line 38 adapted to be connected to the source 10, an inhalation check valve 40, which controls the flow of O_2 into the mask via a nozzle 42, a diffuser section 42a and an outlet 44 connected to the mask inlet/outlet port 34 and to the chest bladder 20 via port 44a. The nozzle 42 and diffuser 42a form an eductor for drawing in cabin air into the O_2 stream entering the mask via duct 46 where the g-force load does not exceed a preselected limit, as will be explained. The inhalation valve 40 includes a flexible diaphragm 40a which engages an annular seat 40b in the closed position, a lower chamber 40c and an upper chamber 40d. As illustrated, both the upper and lower chambers are connected to the high pressure duct with a restricted orifice in

38d located in the portion of the high pressure line leading to the lower chamber 48b. The lower chamber is also connected via pressure relief line 38b to a discharge orifice 48e of a second diaphragm valve 48 which functions to sense the direction of fluid flow in the inlet/outlet port 34 and thereby the initiation of the pilot's inhalation mode as will be explained. The valve 48 includes a flexible diaphragm 48a, a lower chamber 48b connected to the high pressure line 38 via a restricted orifice 38b and an upper chamber 48c connected to the mask inlet/outlet port 34 via passageway 38h as illustrated. A spring 48d normally biases the membrane 48a and its centrally disposed valve member 48f against the seat surrounding the orifice 48e.

The lower chamber of the flow sensing valve 48 is also connected to a lower chamber 50b of an exhalation valve 50 via duct 38c. The exhalation valve (shown in its closed position) when open connects the mask inlet/outlet port to a low pressure region such as the aircraft cabin. The valve 50 includes a flexible diaphragm 50a which engages, in its closed position, an annular seat 50c. The exhalation valve also includes an upper chamber 50d in fluid communication with the inlet/outlet port 34. As will be explained in more detail, when the pressure in the upper chamber exceeds the pressure in the lower chamber 50b by a sufficient amount to overcome the differences in the areas of the diaphragm 50a which are exposed to the upper and lower chambers the valve 50 will open and allow the pilot to exhale.

The lower chamber 50b of the exhalation valve 50 is also connected, via duct 38c to a safety (poppit) valve 52 which sets a limit to the maximum inhalation pressure. In addition, the lower chamber 48b is connected, via a continuation of duct 38c, to (a) the lower chamber 54b of a normally open diaphragm valve 54 which senses the operation of the inhalation valve; (b) the inlet 56a of a minimum inhalation pressure setting valve 56; (c) the inlet 58a of a maximum inhalation pressure setting valve 58, via duct 38d, and (d) the inlet 60b of a cabin vent diaphragm valve 60. A sixth diaphragm valve 62 (when open as shown) connects the passage 46 to the cabin interior via vent port 46a and filter 46b. The lower chambers 60c and 62b of the valves 60 and 62, respectively are in fluid communication with

the anti-g pressure regulator 12 (Fig. 1) via duct 38e so that when the gas from the regulator 12 reaches a predetermined limit, representing a gravitational force of say 2.5 g's, the diaphragms 60a and 62a will overcome the force of bias springs 60d and 62c and engage their respective annular seats to close off the inlet 60b to the cabin vent port 38f via line 38g and also close off the duct 46 from the cabin interior thereby stopping the flow of cabin air into the eductor and mask.

Conventional poppit valve 63 serves as a safety valve to vent the duct 38g (and ducts 38j and 38k) to the cabin interior in the event that vent port 38f becomes plugged. The remaining parts of valves 54, 56 and 58 will be described in conjunction with the following explanation of the operation of the pressure regulating valve block assembly 36.

<u>Operation of the Pressure Regulating Valve Assembly Without Compensation for High-g Loads</u>

In the absence of high g-force loads (e.g., below 2.5 g's) the pressurized O_2 in the inlet duct 38 creates (almost immediately after connection to the supply 10) an equal pressure in the lower and upper chambers 40c and 40d of the inhalation valve 40. As a result of the differences in the surface areas of the diaphragm 50 which are exposed to the two chambers, the inhalation valve is closed as shown in Fig. 5. At the same time O_2 flows, via restriction 38b, ducts 38c, 38d, open valve 60 and vent port 38f to the low pressure region of the cabin (or atmosphere).

The restriction 38b determines the net flow of O_2 to the cabin interior for functional purposes. This net flow may be of the order of about .5 liters per minute (L/min). At the same time the anti-g regulator pressure/valve 12 (Fig. 1) provides a preliminary filling of the anti-g suit's bladders 18a by supplying gas (such as O_2) thereto at a positive pressure of say 6-8 inches of H_20.

When the pilot starts to inhale (i.e., initiation of the inhalation phase) a low pressure is created under the mask and in the inlet/outlet port 34 thereof and at the outlet 44 of the valve block assembly 36. This low pressure is transmitted to the upper chamber 48c, via duct 38h, causing the membrane 48a to overcome the bias

of spring 48d and lift off of the seat surrounding the orifice 48e. As a result the pressure in the upper chamber 40c of the inhalation valve 40 is rapidly reduced. Since the gas O_2 flow through the restriction 40e is a considerably less than the gas flow through the open orifice 48e (by design) the difference in pressure between the upper and lower chambers will cause the inhalation valve 40 to open. The resulting O_2 flow through the nozzle 42 creates a low pressure on the downstream side of the nozzle thereby educting cabin air, via duct 46, open valve 62, duct 46a and filter 46b into the gas stream exiting the nozzle in a conventional manner. It should be noted that where the aircraft is provided with an on board oxygen generator ("OBOG"), which employs outside air to provide an enriched O_2 mixture in lieu of a pressurized O_2 container the passage 46 and valve 62 may be eliminated.

The opening of the inhalation valve also creates a high pressure on the upstream side of the nozzle 42 and in the upper chamber 54c of the valve 54 (via duct 38i) causing the diaphragm 54a to engage seat 54d and close passage 38c from valve 56 and vent 38f. This action does not affect the operation of the regulating valve assembly in the absence of a g-force overload (e.g., in excess of 2.5 g's) since passage 38d and open valve 60 serve as a bypass to vent duct 38c to the low pressure region of the cabin as illustrated.

At the completion of the inhalation phase the low pressure in the upper chamber 48c of the inhalation sensing valve 48 declines to say zero (i.e., rises to about cabin pressure) and the spring 48d biases the diaphragm 48a to again close the orifice 48e thereby allowing the pressure in the lower chamber 40d of the inhalation valve to increase and force the diaphragm 40a to engage its seat 40b. This action closes valve 40, terminating the inhalation phase. The valve 54, which senses the cessation of fluid flow through the nozzle also opens as a result of the pressure in the upper and lower chambers equalizing, but without consequence in the absence of a g-force overload. At the initiation of the exhalation phase the pressure in the inlet/outlet port 34 increases to a level slightly above the cabin pressure (due to pilot's exhalation) forcing the diaphragm 50a away from its seat 50c and exhausting

the exhaled air to the cabin. It should be noted that the exhalation phase as used herein means the time period that the inhalation valve remains closed even though a pilot may not commence exhaling gas at the instant of the inhalation valve closure.

Operation of the Pressure Regulating Valve Assembly with Compensation for High g-force Loads

When the system is subjected to a predetermined g-force overload, say 2.5 g's, the gas pressure in duct 38e (from the anti-g pressure/regulator valve 12) closes valve 62 to cutoff cabin air as a supplement to the O_2 from source 10. This same increased pressure closes valve 60 to cutoff passage 38g as a bypass to valves 58 and 54 thereby setting up the possibility of creating positive maximum and minimum pressures in the mask inlet/outlet port 34 as well as in the chest bladder via port 44a during the inhalation and exhalation phases. It should be noted that valves 60 and 62 need not be arranged to close in response to the same pressure.

Curves 66 and 68 of Fig. 6 represent selected values for the maximum and minimum pressures, respectively, for g-force loads above 2.5 g's. While, as is illustrated in the figure, the curves 66 and 68 are linear for g-forces above 2.5 to 4.0 g's, respectively, the curves need not be linear.

As a result of the closure of valve 60 gas within passage 38c can be vented to the cabin interior only via g-sensing elements 56b and 58b (of valves 56 and 58) which close their respective valve inlets 56a and 58a in response to preselected g-force loads. The g-sensing elements may be in the form of cylindrically shaped weights slidably mounted in cylindrical cavities as illustrated and oriented in a conventional manner to respond to the gravitational forces to which the pilot is being subjected. The g-sensing element 58b defines the maximum positive inhalation pressure and g-sensing element 56b defines the minimum positive pressure in the mask inlet/outlet port 34.

During exhalation under a preselected g-force load, say 2.5 to 4.0 g's, no positive pressure is created in the mask inlet/outlet port 34, because the diaphragm valve 54 remains open and the spring 56c is arranged to prevent element 56b from

closing inlet 56a and interrupting the flow of gas through ducts 38c and 38j to the cabin vent port 38f.

During this same g-force range, the inhalation phase is initiated when the pressure in the mask inlet/outlet port 34 falls to a sufficiently low pressure, say .2 to .25 inches H_20, to overcome the bias of spring 48d and open inhalation valve 40. This low pressure, which is the same as that required without g-force compensation, may be referred to as the threshold of sensitivity. See fig. 7 and particularly point 70a on curve 70 representing a pilot's inhalation and exhalation phases under g-force loads requiring face mask and chest bladder pressure compensation. In this particular case, i.e., g force loads less than a preselected value,[i.e.,] say 4 g's, the minimum pressure (68a on Fig. 7) would essentially be equal to the cabin pressure.

As discussed above, the opening of the valve 40 creates a positive pressure in the upper chamber 54c of the valve 54, thereby closing the valve and cutting off the access of passage 38c to the inlet 56a of valve 56 and the cabin vent port 38f.

At this time a positive pressure is instantly created in the passage 38c. This pressure will rise until it reaches a value sufficient to overcome the resistance of the g-sensing element 58b. At that point in time O_2 will flow through the valve 58, the passage 38k and then to the cabin via vent port 38f. This pressure corresponds to the maximum positive pressure, which will be created in the mask inlet/outlet port 34 and in the chest bladder at the end of the inhalation phase. This positive pressure is transmitted to the lower chamber 48b of the valve 48 and maintains the inhalation valve 40 open until the pressure in the upper chamber 48c achieves the same value and allows the spring 48d to close valve 48 with the consequence that the inhalation valve is also closed terminating the inhalation phase. Curve segment 70b represents the positive pressure buildup in the inlet/outlet port 34 and the chest bladder during the inhalation phase. This same positive pressure exists in the lower and upper chambers 50b and 50c of the exhalation valve 50.

Once the inhalation valve closes the pressure in the upper and lower chambers 54d and 54b equalize and allow the valve 54 to open thereby venting passage 38c to

the cabin via open g-sensing valve 54, duct 38j and vent port 38f.

The pressure in the lower chambers 48b and 50b of valves 48 and 50 also rapidly decline due to the venting of passage 38c, opening the exhalation valve 50 to exhaust the pilot's exhaled air. When the g-force is greater than the selected 4 g's, this pressure declines to a value defined by the resistance of g-sensing element 56b. The pressure, for example, at about 7 g's, may be of the order of about 10 inches H_20 as is illustrated by Fig. 6. Again, as the pressure in the lower chamber 50b of the exhalation valve 50 decreases to the minimum level 68 a (Fig. 7) the exhalation valve opens and gas is released from the pilot's lungs to the cabin with a minimum effort on the part of the pilot. Compare, for example, Figs 4 and 7. It should be noted that the pressure rise gradient, i.e., represented by the angle α in Fig. 7, should (a) be sufficient to provide the necessary maximum pressure in the lungs during a reasonable inhalation time frame and (b) not exceed a rate (maximum value) which would possibly injure the tender lung tissues. As an example, the maximum pressure should preferably not be reached during the initial three-fourths of the inhalation phase.

TEST RESULTS

Tests of the invention were made by subjecting healthy men, in good physical condition, to the g forces indicated via a centrifuge while the men were equipped with conventional anti-g force protection apparatus and with the apparatus of the present invention. The pressure differential (i.e., max vs. min) used was about 16 inches H_20. The individuals performance efficiency was evaluated on the basis of the impairment of their periphery vision angle. An individual's performance capability was considered to be compromised when his peripheral vision became limited to 70°.

The maximum inhalation pressure represented by curve 66 in Fig. 6 may be about the same that was provided by the state of the art anti-g systems relying on the same pressure in the mask for any given g-force load. The minimum exhalation pressure represented by curve 68 in Fig. 6 is preferably within the range of about 14 to 20 and most preferably about 16 to 18 inches of H_20 less than the maximum

inhalation pressure for all g-force loads above a selected minimum, say about 4 g's.

The graphs of Figs. 8a, 8b, and 8c depict the actual breathing cycle of an individual undergoing a test while equipped with the present invention. The graphs, which are self-explanatory, illustrate the rise and fall of the mask inlet/outlet port pressure during the inhalation and exhalation phases when the individual was subjected to the noted g-force loads. These graphs all depict the actual maximum and minimum pressures with a difference thereof of about 16 inches H_20.

The graphs of Figs 9a, 9b and 9c illustrate the typical breathing rate in cycles/minutes of an individual undergoing tests at 5, 7, and 9 g-forces using conventional anti-g equipment (curve A) and the present invention (curve B).

The graphs of Figs. 10a, 10b, and 10c represent an individual's pulse rate at 5, 7 and 9 g-forces using conventional anti-g equipment (curve A) and the present invention (curve B). The graphs of Figs. 11a, 11b and 11c represent an individual's ventilation rate in liters/min at 5, 7, and 9 g-forces using conventional anti-g equipment (curve A) and the present invention (curve B). The tests of Figs. 9, 10 and 11 were terminated when the test individual performance capability was compromised as discussed earlier.

The tests results of Figs. 9 and 10 show that an individual's breathing and heart rate was overloaded considerably when equipped with the state of the art system and remarkably so at 9 g's in contrast to the use of the present invention. The ventilation rate was also considerably higher when using conventional equipment versus the invention as is illustrated in Fig. 11. The duration of satisfactory tolerance time also increased with the invention versus the state of the art equipment. Also, the individuals undergoing the tests with the invention were able to have two-way radio communications.

The maximum pressure gradient α (Fig. 7) during inhalation initially set at 28 inches of H_20/sec. was reduced to 25 inches H_20/sec. to comply with two of the testers complaints that breathing was unpleasant at the higher rate. No complaints were voiced when the rate was reduced.

The test results show that the present invention overcomes many of the short comings of the current state of the art anti-g systems and will enable a pilot to utilize to a much greater extent the performance capabilities of modern aircraft.

<u>The Pressure Regulating Electronic Valve Assembly</u>

An alternative embodiment of the present invention in the form of an electronic/pneumatic valve and pressure regulating system is illustrated in Fig. 12. An on-board oxygen generator ("OBOG") 70 provides pressurized O_2 to the inlet 74a of an inhalation valve 74 located in a housing 76. The outlet 74b of valve 74 is connected to the mask inlet/outlet port 34 via a housing duct 78, and outlet 44. An exhalation valve 82 has an inlet 82a connected to the mask inlet/outlet port via outlet 44 and an outlet 82b in fluid communication with the cabin or low pressure region. The exhalation valve controls the pressure at which air may be exhaled (to the cabin) by the pilot. A pressure transducer 84 senses the pressure in the outlet 44 (and the mask inlet/outlet port) via probe 84a and provides a signal representative of such pressure to a microprocessor or computer 86. A g-sensing element 88, which may be of an electronic accelerometer type, provides a signal to the microprocessor 86 representative of the g-forces to which the pilot is being subjected. The pressure regulating valves 72 and 82 may be of the type in which a solenoid operates a diaphragm to control the magnitude of fluid flow through the valve (and outlet pressure) in accordance with an electric current. One such valve is manufactured by South Bend Controls Inc. of Southbend, Indiana under the part number 27722. Such a valve must be able to accommodate the anticipated high g-forces. The microprocessor is programmed to open and close the valves 74 and 82, respectively, upon the initiation of the inhalation phase via a signal from pressure regulator 84. The microprocessor monitors the pressure and the pressure change in outlet 44 via pressure transducer 84. When the pressure changes in outlet 44 after exhalation by a threshold amount signifying that the pilot has initiated the inhalation phase, the microprocessor applies a signal to input circuit 74c to open the valve and adjust the solenoid current, to cause the pressure at 44 to substantially follow the curve 70b of

Fig. 7. At the same time the microprocessor applies a signal to the input of the exhalation valve 82 to close the same. When the pressure at 44 reaches the selected maximum inhalation pressure for the g-force experienced by the pilot the microprocessor turns off the inhalation valve 74 and opens the exhalation valve 82 via a signal to input circuit 82c to commence the discharge of O_2 within the duct 78. The microprocessor further controls the minimum pressure at which the exhaled air will be discharged through the valve 82. This process repeats itself to supply O_2 to the mask inlet/outlet port from the minimum to the maximum pressure during the inhalation phase and to allow the pressure therein to fall to the minimum pressure during the exhalation phase, thereby greatly decreasing the exhalation effort required by the pilot. It should be noted that a flow sensor may be used to detect the initiation of the inhalation phase in lieu of discerning the change in pressure by the pressure transducer. Since the system of fig. 11 may be programmed to have a faster response time than the pneumatic system of Fig. 5 the exhalation pressure curve may have a faster decay time. However, the rise time of the inhalation curve is limited by a pressure gradient α (Fig. 7) which will not endanger the pilot's lungs.

<u>Optional Nonlinear G-responsive Pressure Regulator for Supplying Pressurized Gas to the Anti-g suit</u>

Current anti-g valves for use in high performance aircraft provide an output pressure schedule that is linear with increasing gravity forces. A typical schedule is shown as curve 24 in Figure 2. There is evidence that an optimal schedule would more nearly follow a non-linear curve depicted by curve 92 in Figure 13.

Such a curve can be implemented through the use of a proportional valve 74 (Fig. 12) in conjunction with a g-sensing element 88 and a controller or microprocessor 86 wherein the flow rate (and outlet pressure) through the valve 74 is controlled via appropriate programming of the microprocessor. It is to be noted that the inlet proportional valve 74 would be connected to a source of pressurized gas from an engine driven compressor, for example, and the outlet would be connected to the anti-g suit bladders.

A single pneumatic pressure responsive regulator for providing pressure regulation characteristics which approximates the curve 92, i.e., that follow two intersecting lines, such as shown by curve CDE, is illustrated in Fig. 13 wherein a flow control valve 94 controls the flow of gas from the pressurized gas source 11 (e.g., 1.5 to 10 Bars) to an anti-g suit (Fig. 1) via inlet passage 96 and outlet port 98. The pressure schedule which simulates a nonlinear curve, e.g., curve 92 through the use of a plurality of straight intersecting line segments over the anticipated g-load range, e.g., C D and D E is also referred to herein as nonlinear.

The control valve 100 includes a diaphragm 100a disposed between upper and lower chambers 110b and 100c, respectively. Chamber 100b receives pressurized gas from the inlet 96 via restrictor 96a with no g-load present. The valve 100 is closed, i.e., diaphragm 100a seats against seat 100 as a result of the diaphragm having a greater area exposed to the upper versus the lower chamber. Gas also flows through restrictor 96b along channel 96c into an upper (reference pressure) chamber 102b of a second diaphragm valve 102 and then through the seat 104a of a first g-load sensing element 104 which element is biased into its open position via spring 104b. The gas, after passing through seat 104a, flows through chamber 106, channel 108, normally open test valve 110, channel 108a and finally to the inlet 112a of valve 112, biased to its closed position via spring 112b.

Valve 112 creates a small positive pressure, e.g., 4 to 8 inches of water, in upper chamber 102b that will cause the diaphragm 102a to move against pilot valve 114. This will cause gas to flow from the upper chamber 100b of the control valve 100 through the pilot valve seat 114a and through channel 98a to the outlet port 98 and the anti-g suit connected thereto. This flow will result in a drop in pressure in the upper chamber 100b due to the action of the flow restrictor 96a which in turn causes the diaphragm 100a to lift off its seat and open the flow control valve 100 and allow gas to flow through the outlet port until the pressure in the outlet port is equal to the pressure in upper chamber 102b of diaphragm valve 102. At this time, the diaphragm 102a moves away from the pilot valve 114, allowing the spring 114a to

close the valve 114. At this same time the pressure in upper chamber 100b equals the supply pressure from source 11 and the flow control valve shuts off flow to the outlet port 96. This initial operation creates a constant positive pressure in the anti-g suit bladders for initial filling. The pressure in a lower chamber 116c of a third diaphragm valve 116 is transmitted from upper chamber 102b through channel 96c and acts to open or close diaphragm valve 116 and flow therethrough to the outlet port so as to maintain the pressure in outlet port 96 approximately equal to the pressure in the upper chamber 102b.

In order to check the performance of the g-responsive pressure regulator assembly of Fig. 14, the pilot presses the test button 110a which closes the flow through channel 108a. Spring biased relief valve 118 then acts to control the pressure in upper chamber 102b. Valve 118 is typically set to open, via spring 118a, at a pressure of 10 to 12 inches of water. A second spring biased relief valve 120 connected to the upper chamber 102b through channel 121 acts, via spring 120a, to limit the pressure in the upper chamber and thus the outlet pressure to a safe maximum level.

Two g-load sensors, i.e., 104 and 122 are connected in parallel to control the reference pressure in upper chamber 102b. Sensor 104 consisting of weight 104c and spring 104b produces a pressure schedule as shown by curve C F in Fig. 15. Sensor 122, via weight 122c and spring 122b produces a pressure schedule as shown by curve G E, i.e., gas will flow through its inlet 122a when the pressure in the upper chamber 102b is sufficient to lift the weight as biased downwardly by spring 122b, off of its seat 122a. The resulting reference pressure in chamber 102b (and in the outlet 99) will be the lessor of the two schedules as shown by curve C D E in Fig. 15. The chamber 106 is sometimes hereinafter referred to as a low pressure region.

It is to be noted that rate of pressure increase in the anti-g suit is higher during acceleration from low g loads to intermediate g loads, i.e., from C to D in Fig. 15 and at a lower rate during acceleration from intermediate g loads to high g loads, i.e., D to E in Fig. 15.

There has been described a novel method and apparatus for regulating the inhalation and exhalation of breathable gas, such as O_2 or a mixture of O_2 and air, to and from a pilot's lungs while the pilot is equipped with an anti-g force suit, a face mask with a common inlet/outlet port and an inflatable chest bladder during high-g maneuvers. Optionally the anti-g suit may be inflated at a nonlinear pressure schedule. The invention greatly reduces the stress imposed on a pilot when breathing at high g-force loads thereby enabling the pilot to comfortably withstand high g-force loads for an extended period. As a result, a pilot can more fully accommodate the high performance characteristics of modern aircraft and space ships. Various modifications of the particular embodiments disclosed herein will become apparent to those skilled in the art without involving any departure from the spirit and scope of the invention as defined by the appended claims.